PLANETARY NEBULAE WITH BINARY NUCLEI

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ABSTRACT

Planetary nebulae with close binary nuclei are reviewed. It is shown that these systems can be used as a source of information for the physics of the common envelope phase in the evolution of binary systems. Mechanisms for the production of bipolar planetary nebulae are examined and it is concluded that presently the action of binary companions to the central stars appears to provide the most promising mechanism. Other systems (e.g. novae, supernovae) in which similar processes may be operating are discussed.

1. INTRODUCTION

The existence of planetary nebulae (PNe) with close binary nuclei can be regarded as the most direct evidence for the occurrence of common envelope (CE) phases in the evolution of binary systems (e.g. Paczynski 1976; Ostriker 1975; Livio, Salzman and Shaviv 1979 and see Bond, Ciardullo and Meakes 1992 for a recent review). The occurrence of a CE phase in classical nova systems will be discussed separately in section 3.

A compilation of all the PNe with confirmed *close* binary nuclei is given in Table 1 (adapted from Bond and Livio 1990). Three more objects which surely contain binary (or possibly triple) nuclei are given in Table 2. In the latter case, however, the observed periodic photometric variations almost certainly represent the rotation periods of the cool stars (Bond, Ciardullo and Meakes, private communication) and thus, the orbital periods remain unknown. It has been suggested that LoTr 5 is a triple system (Jasniewicz *et al.* 1987; Malasan *et al.* 1991), with the internal binary having a period of about 2 days or 1.75 days (Jasniewicz and Acker, this volume, Malasan *et al.* 1991). This conclusion however,

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Table 1. Planetary Nebulae with Close Binary Nuclei (adapted from Bond and Livio 1990)

Planetary Nebula	Central Star	Orbital Period (days)
A41	MT Ser	0.113
DS1	KV Vel = LSS 2018	0.357
A63	UU Sge	0.465
A46	V477 Lyr	0.472
HFG 1	V664 Cas	0.582
K1–2	VW Pyx	0.676
A65		1.00
HtTR 4		1.71
Sp 1		2.91
NGC 2346	V651 Mon	15.99

Table 2. Planetary Nebulae with Binary Central Stars Which Show Photometric Variability Which Probably Represents the Rotation Period of the Cool Star (from Bond, Ciardullo and Meakes, private communication)

Planetary Nebula	Central Star	Period of Optical Variability (days)
A35	LW Hya = BD−22°3467	0.76
LoTr 1		3.3 or 6.6
LoTr 5	IN Com = HD 112313	5.9

should be re-examined, because of the fact that the rotation period of the cool star (with a period of about 5.9 days) coupled with amplitude variations that are probably due to star spots, may generate apparent false periodicities. The suggestion that Sh2–71 has a period of $P = 68^{d}\!.06$ (Jurcsik, this volume) is presently not confirmed by observations of Bond (private communication). More observations on this object are needed. Two other suggestions for nebulae with binary central stars need to be mentioned. The central star of M1–67 (which is suggested to be a PN, van der Hucht *et al.* 1985), QR Sge ≡ 209 BAC, is a binary with a period of 2.358 days (Moffat *et al.* 1982). However, the nebula in this case was only identified in the infrared and the central star is a Wolf-Rayet object. Thus, this object is probably more similar to rings around massive stars (see Chu, this volume) than to ordinary PNe. The central star of PK 331–5°1 (PC 11, HD 149427) was also found to be a binary (Parthasarathy, Pottasch and Clavel, this volume). However, this system was also identified as a D-type symbiotic star.

A few new observations of known binary central stars should be mentioned. These include observations of UU Sge (Pollacco and Bell 1992; Malasan and Yamasaki 1992 and Walton, Walsh and Pottasch, see this volume), HFG 1 (Malasan and Yamasaki 1992), A 46 and A 65 (Walsh, Walton and Pottasch, this volume) and x-ray observations of LoTr 5 (Kreysing *et al.* this volume).

The main thing to note about *all* the objects in Table 1 (and possibly in Table 2) is that *they had to undergo CE evolution*! Indeed, all binaries containing at least one compact component with orbital periods satisfying $P_{orb} \lesssim$ days, which are not located in very dense clusters (and therefore are probably not capture products), had to pass through a CE phase in order to be formed.

2. A BRIEF DESCRIPTION OF THE PHYSICS OF THE CE PHASE

Common envelope is considered to be an essential phase in the formation of such objects as cataclysmic variables, binary pulsars and at least some x-ray binaries (e.g., Eggleton and Tout 1989; Tutukov, Yungelson and Iben 1992). One of the scenarios leading to Type Ia supernovae involves the merger of two white dwarfs and requires one (e.g., Webbink 1984) or two (e.g., Iben and Tutukov 1984) CE phases.

The occurrence of a CE phase is supposed to be often the result of *a dynamical mass transfer event.* This, in turn, can be the consequence of the following two things happening together:

(1) Mass being transferred from the more massive to the less massive component (it is easy to show that this leads, if mass and angular momentum are conserved, to a reduction in the binary separation).

(2) The mass losing star has a deep convective envelope (as in the AGB phase; in this case the star tends to expand when losing mass).

These two conditions lead to a situation in which the mass losing star cannot contract as rapidly as its Roche lobe and an unstable mass transfer ensues (e.g. Paczynski and Sienkiewicz 1972; Edwards and Pringle 1987). The high mass transfer rate (which can exceed the Eddington limit) overwhelms the secondary star, and drives it out of thermal equilibrium. The secondary starts expanding and the system rapidly evolves into a CE configuration (e.g. Yungelson 1973; Webbink 1977; Prialnik and Livio 1985).

The main effect of the CE is to reduce the binary separation by the drag which the two components experience, while the gravitational energy can be deposited (in some cases) into the ejection of the common envelope. Thus, we immediately realize that the final outcome of the CE phase is determined mainly by the efficiency with which orbital energy is deposited into mass ejection. This efficiency is conveniently expressed by the parameter (Tutukov and Yungelson 1979; Livio and Soker 1988)

$$\alpha_{CE} \equiv \frac{\Delta E_{bind}}{\Delta E_{orb}} \tag{1}$$

where ΔE_{bind} represents the binding energy of the ejected material and ΔE_{orb} is the total change in the binary's orbital energy. A value of $\alpha_{CE} = 1$ means that every ejected mass element receives (from orbital energy) exactly the energy it needs for escape.

One of the most important tasks of the study of CE evolution is to determine the value of α_{CE}, both using observations and theoretically.

At least two processes can act to reduce the value of α_{CE}:

(1) Efficient energy transport
(2) Non-spherical effects.

The first effect is important in situations in which the timescale for energy transport is short compared to the orbital decay timescale. In such cases, the energy that is released by the decay of the orbit is transported to the surface and radiated away without causing almost any mass motions (e.g. Meyer and Meyer-Hofmeister 1979). Such situations can arise when the secondary is of a very low mass (e.g. a brown dwarf, Livio and Soker 1984), or in the very outer layers of CE configurations resembling AGB stars. In both of these cases, the drag luminosity represents only a small perturbation to the star's own luminosity.

The second effect ((2) above) which can reduce the value of α_{CE} is related to the fact that multi-dimensional numerical hydrodynamic calculations revealed that *mass is ejected preferentially in the orbital plane* (e.g. Taam and Bodenheimer 1989, 1991; Livio and Soker 1988 and see Fig. 1). This has the effect that only a part of the envelope mass, is given more energy than it needs to escape, thus reducing the overall efficiency. In the hydrodynamical calculations, values of α_{CE} in the range 0.3–0.6 were obtained.

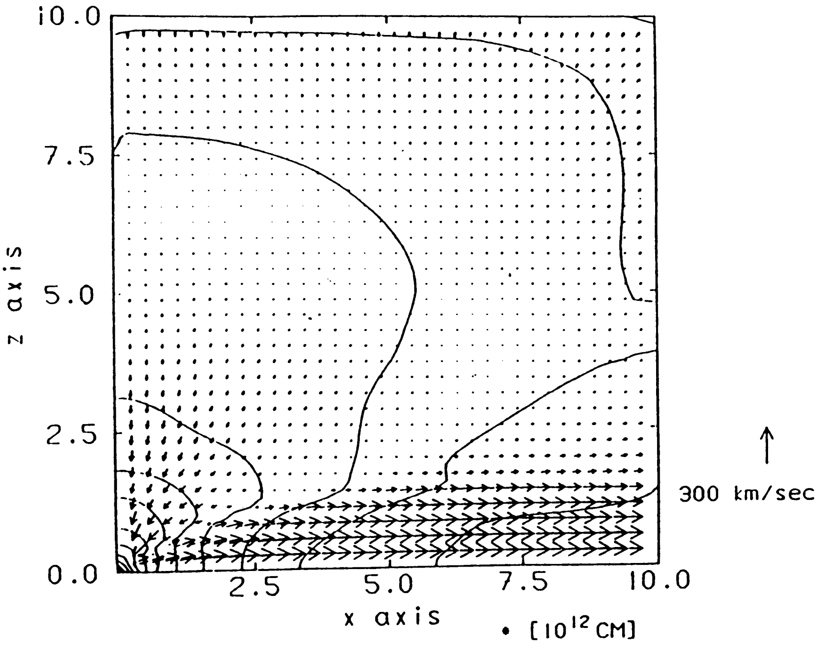

Figure 1. The velocity field and density contours in a common envelope calculation. The z axis is perpendicular to the binary's orbital plane. From Taam and Bodenheimer (1989).

In principle, one could consider other energy sources which can contribute to envelope ejection during the CE phase, while retaining the formal definition of α_{CE} as in eq. (1). If such additional sources indeed participate in the ejection of the envelope, then this could result in values of α_{CE} that are even larger than unity.

Processes during the CE phase that can (in principle) increase the value of α_{CE} are:

(1) Spin-up of the envelope and the dynamo generation of magnetic fields (see section 4).

(2) The excitation of non-radial modes (e.g. Soker 1992a, b, and see section 4).

(3) The tapping of the recombination energy in the hydrogen and helium ionization zones (originally suggested for PN ejection by single stars, Paczynski 1967).

(4) The injection of new fuel (e.g. hydrogen into the helium burning shell) by circulations which develop in the CE (e.g. Taam and Bodenheimer 1989).

Until now, none of the above processes was included in CE calculations, thus their actual effect on the value of α_{CE} is still unknown.

In order to obtain an idea of the reduction in the separation that can be expected for a typical cataclysmic binary progenitor, we can crudely estimate ΔE_{bind} and ΔE_{orb} in eq. (1) to obtain

$$\frac{GM_1^2}{a_i} \simeq \alpha_{CE} \frac{GM_{1R}M_2}{a_f}, \tag{2}$$

where M_1, M_2 are the initial masses, a_i and a_f are the initial and final separations (respectively) and M_{1R} is the remnant mass of the primary, following the CE phase. This leads for typical parameters to a final separation of

$$a_f \simeq 2.4 R_\odot \left(\frac{\alpha_{CE}}{0.4}\right) \left(\frac{M_{1R}}{M_\odot}\right) \left(\frac{M_2}{0.3\ M_\odot}\right) \left(\frac{M_1}{5\ M_\odot}\right)^{-2} \left(\frac{a_i}{500\ R_\odot}\right). \tag{3}$$

3. PLANETARY NEBULAE WITH BINARY NUCLEI AND COMMON ENVELOPE PHYSICS

Because of the fact that the existence of PNe with close binary nuclei can be regarded presently as the closest to direct evidence for the occurrence of a CE phase, these objects provide us with the best source of information on the physics of the CE. PNe with binary central stars can be used in this respect in at least three ways:

(i) Using assumptions about the distribution of binary systems in primary masses, in initial separations and initial mass ratios, together with some assumptions about CE evolution, it is possible to calculate the expected distribution in the masses of the two components of the binary central stars, in their orbital periods, etc. This approach was used by de Kool (1990) and by Yungelson and Tutukov (this volume). In principle, the obtained distributions can be used (by comparison with the observed objects) to place constraints on α_{CE}. However, the small number of objects that is presently known is not sufficient to enable us to place meaningful constraints yet.

(ii) A second method (Iben and Tutukov 1989) used similar assumptions as in (i) above, in combination with attempts to reconstruct the evolutionary path of V651 Mon, LSS 2018, MT Ser and UU Sge (Table 1), in order to obtain a semi-empirical determination of α_{CE}. Unfortunately, uncertainties in the binary parameters of the systems (as well as in the theoretical evolutionary paths) do not allow yet firm conclusions to be drawn. This is, however, a potentially very promising approach.

(iii) Observations of the morphology of the PNe with binary nuclei can provide tests for both the CE phase and the "interacting winds" (Kwok 1982; Kahn 1982) model for the shaping of the nebulae.

As explained in section 2, the ejection of the CE occurs mainly in the orbital plane (within ~ 12°). This produces a "density contrast" between the equatorial (orbital plane) and polar directions. In the interacting winds model, the fast and dilute wind that is emitted by the hot, exposed nucleus, runs into the slowly moving material, shocks it and snowplows into it. Balick (1987, and see this volume) proposed a simple morphological scheme in which PNe are divided into three basic types: round, elliptical and butterfly. The key parameter in this scheme is the density contrast between the equatorial and polar directions. A moderate contrast results in an elliptical morphology while a high contrast in a "butterfly." The pioneering, exploratory hydrodynamic calculations of this interacting winds scenario performed by Soker and Livio (1989) and the much more accurate and refined recent calculations by Icke *et al.* (1992), Frank *et al.* (this volume) and Mellema *et al.* (1991), have shown that it is indeed possible to reproduce many of the observed morphology characteristics (see also Dyson, this volume). Bond and Livio (1990) presented (or provided reference to) imagery of all the PNe with close binary nuclei and showed that the observed morphologies are consistent with the expectations based on the density contrast generated by CE evolution (e.g. Fig. 2).

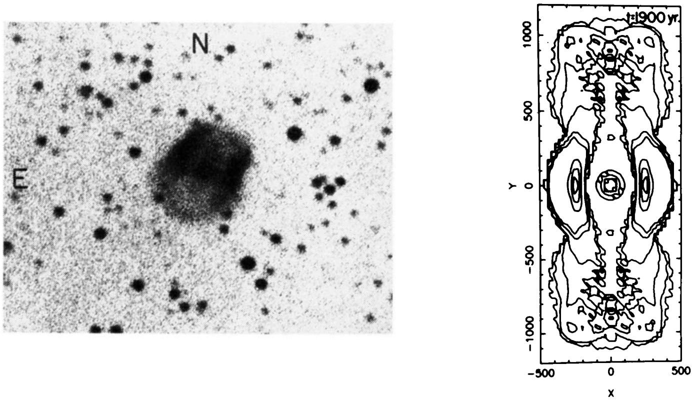

Figure 2. Left panel: direct photograph of Abell 41 (from Grauer and Bond 1983). Right panel: density contours obtained from interacting winds, when a density contrast exists between the equatorial (horizontal) and polar directions (from Soker and Livio 1989).

It is interesting to note that the image of NGC 2346 shows a striking similarity to that of supernova 1987A (Fig. 3, see also Panagia *et al.* 1991). The possibility of a bipolar morphology for SN 1987A was anticipated by Soker and Livio (1989). It is therefore not very surprising that in a recent review, Podsiadlowski (1992) concludes that it is most likely that the progenitor of SN 1987A had a binary companion.

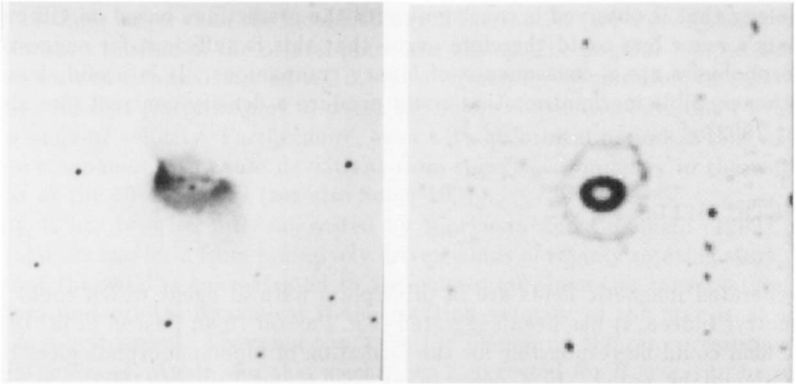

Figure 3. Left panel: Hα CCD image of NGC 2346 (from Bond and Livio 1990). Right panel: deconvolved nebular image of SN 1987A in [OIII] $\lambda 5007$ (from Wampler *et al.* 1990).

Another class of objects (known to be binaries) that experience a short CE phase are classical novae. We note the following properties:

(1) Classical nova systems are binaries with orbital periods of the order of a few hours, implying separations of the order of a solar radius.
(2) Classical novae at maximum are characterized by luminosities of the order of the Eddington luminosity, which for typical white dwarf masses imply a luminosity of order $L \sim (2-5) \times 10^4\ L_\odot$.
(3) The effective temperatures of novae at maximum are of order $T_{eff} \lesssim 10^4$ K.

Properties (2) and (3) above, result in photospheric radii in excess of 4×10^{12} cm, much larger than the orbital separation. Therefore, *the secondary star is necessarily engulfed in the expanding nova envelope.* An examination of nova light curves reveals that some novae remain in this CE phase for periods of months. It should be noted, however, that the mass of the nova envelope is very low, typically of order $\Delta M_{env} \sim 10^{-4}\ M_\odot$. Thus, the density contrast that can be generated by mass ejection that is induced by the engulfed binary companion is never extreme. On the basis of our discussion of the morphologies that can be expected from an interacting winds scenario, one could therefore expect some nova shells to exhibit an elliptical (prolate) morphology. This is indeed the case for some novae (e.g. DQ Her, Barden and Wade 1988; Wade 1990).

4. MECHANISMS THAT CAN PRODUCE A DENSITY CONTRAST

In section 2 I described numerical calculations which demonstrated (admittedly, under-simplifying assumptions) that binary companions can generate the density contrast in the slow wind that is required for bipolar or "butterfly" morphologies. I also presented evidence showing that in the cases in which close binary companions are known to exist, the morphology that is observed is consistent with the predictions based on CE evolution. Using Occam's razor one could therefore argue that this is sufficient for suggesting that bipolar morphologies are a consequence of binary companions. It is useful, however, to examine other possible mechanisms that could produce a density contrast (see also Soker and Harpaz 1992).

4.1. MAGNETIC FIELDS

Dynamo generated magnetic fields are in principle a natural agent which could produce axial symmetry. Indeed, it has been suggested (e.g. Pascoli 1990; Pascoli *et al.* 1992) that a magnetic field could be responsible for the formation of bipolar morphologies. However, two things should be noted. In a recent work, Tout and Pringle (1992) estimated the strength of the azimuthal magnetic field obtained in fully convective stars. Using their formalism one obtains for an AGB star (with $M = 1\ M_\odot$, $R = 400\ R_\odot$, $L = 7000\ L_\odot$) rotating at 10% of its break-up angular velocity, an azimuthal field of $B_\phi \sim 80$ G, which is more than an order of magnitude lower than the field required in the model of Pascoli (1990). Furthermore, Pascoli *et al.* (1992) actually *assumed* the ejection of an equatorial torus with a large scale azimuthal field, rather than showing that such a configuration (which is incidentally unstable) is indeed obtained.

Thus, it is probably fair to conclude at this point that while magnetic fields may play a role in the production of the observed axial symmetry, this has not been demonstrated yet. In fact, a considerable spin-up of the AGB star is probably necessary for dynamo generated magnetic fields to play an important role. Amusingly enough, such a spin-up could be provided by a secondary companion (see below). This may mean that a binary companion is required for magnetic effects to be important.

4.2. NON-RADIAL p-MODES

It has been suggested that towards the end of the AGB phase, non-radial oscillations of the star become more important, potentially leading to axisymmetric mass loss (Soker and Harpaz 1992). This is supposed to happen as a consequence of the fact that the transition region (between the inner envelope, where the oscillations are quasi-adiabatic and the outer envelope, where they are highly non-adiabatic) for the non-radial modes moves inwards, towards the hydrogen ionization zone, thus leading possibly to an increased driving. Soker and Harpaz (1992) did conclude, however, that in order for the non-radial modes to lead to a substantial equatorial (or polar) mass ejection, a relatively rapid rotation (which could be induced by a binary companion) is needed.

4.3. EFFECTIVENESS OF BINARY COMPANION

In order to appreciate the effectiveness with which a binary companion can produce axially symmetric effects in the CE phase it is sufficient to examine the following few numbers. A companion of 0.1 $M_\odot$ that is spiralling inside a configuration corresponding to an AGB star of mass 0.94 $M_\odot$ (core mass of 0.59 $M_\odot$) and radius 350 $R_\odot$, at a distance of 10 $R_\odot$ from the center, can produce a drag luminosity that is as high as 10^5 $L_\odot$. Since this luminosity is about 16 times larger than the local Eddington luminosity (for a given AGB star model), significant mass motion in the orbital plane can ensue. The angular momentum that such a companion can deposit into an AGB star's envelope (by spiralling-in from the stellar radius) is sufficient (in principle) to cause the entire convective envelope to rotate at the break-up angular velocity. Furthermore, even with an orbital period as long as 10000 yrs, a massive companion can cause deviations from spherical symmetry in the wind from the AGB star at the 10–20% level (see also Soker 1991).

Finally, it has been recently suggested by Bjorkman and Cassinelli (1992), that dense equatorial disks can form from radiatively driven winds of rapidly rotating stars. They have shown that the wind is concentrated to the equatorial plane (by conservation of angular momentum and orbital dynamics) if the rotation velocity of the star is at least about half the break-up speed. The wind shocks in the plane and the ram pressure confines the equatorial material. Again, for this mechanism (suggested for B stars) to be operative in AGB configurations, a very significant spin-up of the star has to occur. The most natural way to produce such a spin-up is via a binary companion.

5. INCIDENCE OF RELATIVELY CLOSE BINARY CENTRAL STARS

Out of 108 planetary nebula central stars that have been searched for binarity, 10–14 objects (Tables 1 and 2) proved to be close binary nuclei (Drummond 1980; Drilling 1985; Bond and Grauer 1987; Bond and Ciardullo (ongoing)). This is a slightly lower fraction than the one expected on the basis of the following finding. The search for multiplicity in 164 primaries with spectral types F7–G9 (Duquennoy and Mayor 1991) found that 61% of them have companions (with masses larger than about 0.1 $M_\odot$) and about 28% of those have separations that are smaller than 1000 $R_\odot$. Thus, about 17% of all of these primaries can interact through a CE evolution phase.

I should note that even very low mass companions (e.g. brown dwarfs) can produce significant deviations from spherical symmetry, although more massive secondaries are probably required in order to produce a very pronounced bipolar morphology.

6. SUGGESTIONS AND DISCUSSION

On the basis of the discussion in the previous sections the following suggestions (I think it may be premature to call them "conclusions") emerge:

(1) The central stars of all the PNe that show a clear axial symmetry may have (or had) binary companions. In this respect it is important to note that in the calculations of Yungelson and Tutukov (this volume), mergers of the central star with the companion (especially low mass companions) occur at a rate of 0.12/yr (the total rate of CE

events is 0.5/yr). Thus, even PNe that presently appear to have single central stars may either have very low mass companions or may have had binary companions in the past (mergers in fact have been suggested to occur for EGB 5 and PHL 932, Mendez *et al.* 1988a, b).

(2) Clear "bipolar" or "butterfly" morphologies probably result from relatively massive secondaries (what is really important is the ratio $M_{secondary}/M_{envelope}$) and/or common envelope phases that occur when the primary is in a relatively less evolved AGB configuration (this produces a higher density contrast). Zuckerman and Gatley (1988) found that "butterfly" PNe are more concentrated to the galactic plane than PNe in general. An examination of their statistics and the more recent statistics obtained by Stanghellini (private communication and this volume), reveals only a rather marginal effect. However, such a finding (if confirmed) is consistent with the above discussion. Massive secondaries (needed for "butterfly" morphologies, see above) tend to be associated (in the statistical sense) with relatively more massive primaries. It could therefore be expected that such systems will be more concentrated to the plane.

A very important aspect of bipolarity is the occurrence of "jets" in some objects. The most spectacular examples of such jets were found by Schwarz and co-workers (see e.g. NGC 6309, Corradi and Schwarz, this volume), but a few were known previously (see e.g. K1–2, Bond and Livio 1990; Lutz and Lame 1989).

The important thing to note here is that although the mechanism for jet formation (e.g. in AGNs and young stellar objects) is not entirely clear yet, there seems to be a general concensus that it requires the presence of an accretion disk (e.g. Pringle 1992). The presence of such disks has been advocated by Morris (1987) for some time. In fact, the observations of Corradi and Schwarz and those of K1–2 are consistent with the presence of a precessing jet (incidentally, the similarity with some AGN jets is quite striking).

(3) Classical novae provide an excellent opportunity to study CE physics.

(4) The carbon star V Hya, an AGB star which is rapidly rotating and which shows evidence for a bipolar structure in its circumstellar envelope, may represent the exciting possibility of a common envelope phase in progress (Kahane *et al.* 1992).

(5) It is extremely important to attempt to determine observationally the masses of both components for all binary central stars. This will provide invaluable information for the testing of CE theory.

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